Standard Model:

Getting There and Beyond

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Classical mechanics

- angular momentum $\gg \hbar$
- speed $\ll c$

Quantum mechanics

- any angular momentum
- speed $\ll c$

Special relativity

- angular momentum $\gg \hbar$
- any speed

Quantum field theory

- any angular momentum
- any speed

High Energy Physics has established that all known natural phenomena can be described by a local quantum field theory which is invariant under:

- **3+1 dimensional Lorentz transformations, $SO(3,1)$, and translations.**
- $SU(3)_C \times SU(2)_W \times U(1)_Y$ **gauge transformations**

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$\Longrightarrow$ *all elementary particles belong to certain representations of the Lorentz and gauge groups:*

Spin-1 bosons

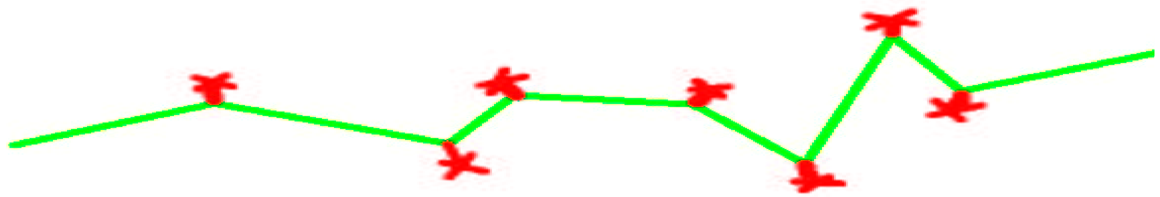
$$\begin{cases} G^\mu : & (8, 1, \ 0) \\ W^\mu : & (1, 3, \ 0) \\ B^\mu : & (1, 1, \ 0) \end{cases}$$

Spin-1/2 fermions

$$3 \times \begin{cases} q_L : & (3, 2, \ +1/6) \\ u_R : & (3, 1, \ +2/3) \\ d_R : & (3, 1, \ -1/3) \\ l_L : & (1, 2, \ -1/2) \\ e_R : & (1, 1, \ -1) \end{cases}$$

Electroweak symmetry breaking

The vacuum is partially opaque to the W and Z.



$SU(2)_W \times U(1)_Y$ gauge symmetry of the Lagrangian is spontaneously broken down to $U(1)_{\rm em}$.

The ground state of our universe is a "superconductive" vacuum!

Parameters of a quantum field theory:

- **masses (dimensionfull)**
- **couplings (dimensionless, $c = \hbar = 1$)**

Experiments measure parameters

or **discover new particles**

or **discover deviations from quantum field theory.**

Examples of measurements:

- ⋆ $\sin^2\theta_W$ **at NuTeV**
- ⋆ **CP asymmetries in** B_s **decays at BTeV**
- ⋆ θ_{13} **at MINOS**
- ⋆ $Br(K^+ \to \pi^+ \nu\overline{\nu})$ **at CKM**
- ⋆ **...**

Examples of discoveries of new particles:

- ⋆ **Top quark at CDF/D0 (Run I)**
- ⋆ **Tau neutrino at DONUT**
- ⋆ **Next bump in** $\sigma(p\bar{p} \to \mu^+\mu^- X)$ **in Run II,**
or in $\sigma(e^+e^- \to \mu^+\mu^-)$ **at a future linear collider**
- ⋆ **...**

Examples of possible deviations from local quantum field theory:

⋆ **If MiniBoone will observe different oscillations for ν and $\overline{\nu}$: violation of CPT and perhaps non-locality** (G. Barenboim, J. Lykken, hep-ph/0210411)

⋆ **If black holes or winding modes will be produced at the LHC: quantum gravity at the TeV scale**

⋆ **...**

Complications:

quantum field theory at strong coupling

Example:

BaBar discovery of a narrow resonance at 2.317 GeV in the $D_s^+\pi^0$ final state $\Longrightarrow$ New particle! (April 12, 2003)

Heavy quark effective theory + model of chiral symmetry breaking in QCD (Bardeen, Eichten, Hill, hep-ph/0305049 - May 5):

$c\bar{s}$ bound state – not a new *fundamental* particle.

$\Rightarrow$ there must also exist an excited D_s^{*+} state of 2.46 GeV

... discovered by CLEO (May 12, 2003).

“High-precision lattice QCD confronts experiment”

HPQCD, UKQCD, MILC and Fermilab Lattice Collaborations: hep-lat/0304004

Masses and matrix elements of long-lived hadrons:

agreement to within errors of $\sim 5\%$.

If a new strongly coupled interaction will be discovered:

theoretical predictions will require improved tools

(*e.g.*, nonperturbative effects of supersymmetric gauge interactions, ...)

Fundamental parameters

Mass scales:

- **Electroweak scale:** $\langle H \rangle \approx 174$ **GeV**

(Vacuum expectation value which breaks the $SU(2)_W \times U(1)_Y$ symmetry; determines M_W, M_Z up to a gauge coupling)

- **Planck scale:** $M_P \approx 2 \times 10^{19}$ **GeV**

(determines the strength of the gravitational interactions)

- **Cosmological constant:** $\approx 10^{-3}$ **eV**

(sets the acceleration of the expansion of the Universe)

Gauge couplings:

- $g_s \longrightarrow \Lambda_{\rm QCD} \approx 100$ **MeV**
- $g, g' \longrightarrow \alpha_{\rm em}\,,\ \sin^2\theta_W$

Fermion couplings to $\langle H \rangle$:

- $\lambda_u^{ij}, \lambda_d^{ij} \longrightarrow$ quark masses and CKM elements
- $\lambda_e^{ij} \longrightarrow$ charged lepton masses

QCD θ parameter:

- coefficient of $G\tilde{G}$ in the Lagrangian: $\theta < 10^{-9}$

(leads to CP-violating quark masses;
measured by the neutron electric dipole moment)

Neutrino masses and mixings:

- *Either* couplings of new particles (ν_R) to $\langle H \rangle$,

  or a new mass scale, $\frac{C_{ij}}{M_{\rm new}}(L^i H)(L^j H)$,

  or both?

Higher-Dimensional Operators

Suppressed by some mass scales $\gtrsim 1$ TeV

If non-zero coefficients $\Rightarrow$ "New Physics"

EXAMPLES:

- $$\frac{C_1}{M_1^2}\left(\bar{l}_L^2\gamma^\alpha l_L^2\right)\left(\bar{q}_L^1\gamma_\alpha q_L^1\right) = \frac{C_1}{M_1^2}\left(\bar{\nu}_L^\mu\gamma^\alpha\nu_L^\mu\right)\left(\bar{u}_L\gamma_\alpha u_L + \bar{d}_L\gamma_\alpha d_L\right) + \ldots$$

  NuTeV measured a combination of $\frac{C_1}{M_1^2}$ and $\sin^2\theta_W$.

- $$\frac{C_2}{M_2^2}\left(\bar{q}_L^3\gamma^\alpha q_L^2\right)\left(\bar{q}_L^3\gamma_\alpha q_L^2\right) = \frac{C_2}{M_2^2}\left(\bar{b}_L\gamma^\alpha s_L\right)\left(\bar{b}_L\gamma_\alpha s_L\right) + \ldots$$

  induces B_s^0-$\overline{B}_s^0$ mixing; to be measured by D0, CDF.

- $$\frac{C_3}{M_3^2}\left(\langle H\rangle\sigma^i W_\alpha^i\langle H\rangle\right)\left(\langle H\rangle\sigma^{i'} W^{\alpha i'}\langle H\rangle\right)$$

  shifts M_W/M_Z, changes the electroweak fits.

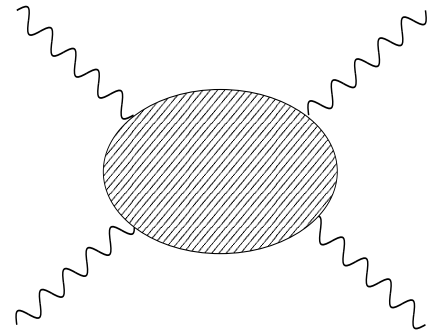
- ...

What else can we expect?

Outline of the talk:

- **What is the Standard Model**
- **What new particles could be there**
- **Towards new underlying principles**

$W_L^+ W_L^-$ scattering:



Perturbatively: $\sigma\left(W_L^+ W_L^- \to W_L^+ W_L^-\right) \approx \dfrac{G_F^2\, s}{16\pi}$

This makes sense only up to $\sqrt{s} \sim 1$ TeV.

At higher energy scales:

⋆ A new particle: Higgs boson

or

⋆ New strong interaction (perturbative expansion not valid)

or

⋆ Quantum field theory description breaks down

Elementary particles "observed" in experiments:

$$\textbf{leptons}\left\{\begin{array}{ccc} \begin{pmatrix}\nu_L^e \\ e_L\end{pmatrix} & \begin{pmatrix}\nu_L^\mu \\ \mu_L\end{pmatrix} & \begin{pmatrix}\nu_L^\tau \\ \tau_L\end{pmatrix} \\ e_R & \mu_R & \tau_R \end{array}\right.$$

$$\textbf{quarks}\left\{\begin{array}{ccc} \begin{pmatrix}u_L \\ d_L\end{pmatrix} & \begin{pmatrix}c_L \\ s_L\end{pmatrix} & \begin{pmatrix}t_L \\ b_L\end{pmatrix} \\ u_R & c_R & t_R \\ d_R & s_R & b_R \end{array}\right.$$

(spin 1/2)

$\overbrace{SU(3)}^{}$ $\times SU(2) \times U(1)$ **gauge bosons** **(spin 1)**

$\text{8 gluons} + W^{\pm}, Z, \gamma$

longitudinal $W^{\pm}$, Z **(spin 0)**

Standard Model

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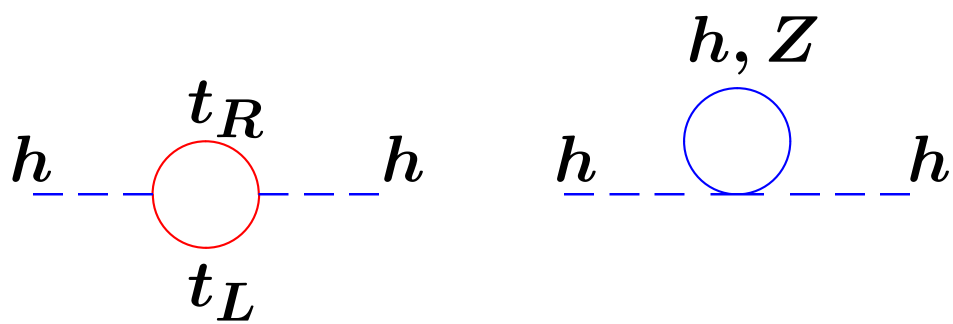
longitudinal $W^\pm$, Z **(spin 0)**

$+ \; h^0$ **(spin 0)** **yet to be discovered**

Physics beyond the Standard Model

Quantum fluctuations tend to increase the vacuum expectation value of the Higgs field.



The stability of the electroweak scale requires a modification of the Standard Model at energy scales above ~ 1 TeV.

$\sim$ 500 B.C. Pythagoreans theorize that the Earth is round

$\sim$ 250 B.C. Erathostenes measures the Earth size with an error of a few %.

140 A.D. Ptolemy draws the World map using a size smaller by 30%.

1482 A.D. World map:

1492 A.D. Columbus performs an experimental test, and concludes that the theory is correct ... But in fact, he discovered something else!

Replica of the detector:

Supersymmetric Standard Model

Many new particles, many new parameters

$\longrightarrow$ prototype for "New Physics"

Nice theoretical features:

- No quadratic divergences ($\langle H \rangle \sim M_{\mathrm{SUSY}}\,,\, \mu$)
- Gauge couplings unify
- Lightest superpartner is a dark matter candidate
- ...

Grand Unification

$$SU(3)_C \times SU(2)_W \times U(1)_Y \subset \ SU(5) \subset \ SO(10)$$

Fermions:

$$\left.\begin{array}{rl} q_L : & (3, 2, \ +1/6) \\ u_R : & (3, 1, \ +2/3) \\ d_R : & (3, 1, \ -1/3) \\ l_L : & (1, 2, \ -1/2) \\ e_R : & (1, 1, \ -1) \end{array}\right\} \times 3 \subset (10 + \bar{5}) \times 3 \ \subset \ 16 \times 3$$

Minimal $SU(5)$: too fast proton decays

Minimal $SO(10)$: typically small ν mixing angles

$\Longrightarrow$ keep looking...

Vector-like quarks

$q_L\,,\,q_R$: same gauge charges

Predicted in many models:

- "Top-quark seesaw" model (Dobrescu, Hill, 1997)

  $\longrightarrow$ Higgs doublet is composite

- "Little Higgs" models (Arkani-Hamed et al, 2002)

  $\longrightarrow$ no quadratic divergences at 1-loop

- "Beautiful mirrors" (Choudhury, Tait, Wagner, 2001)

  $\longrightarrow$ explains $A^b_{\rm FB}$;

  $\longrightarrow$ signal in Run II: $b' \to bZ$ for $m_{b'} < 300$ GeV

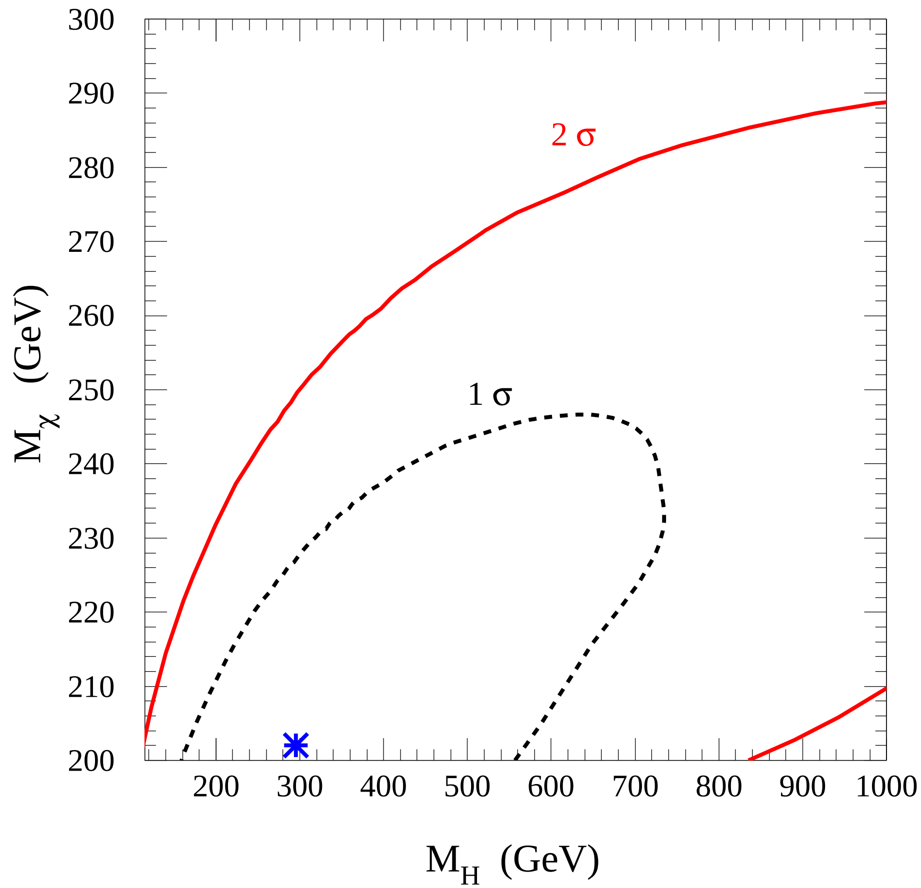
Standard Mirrors: Best Fit

(From: Tim Tait JETP talk, May 2003)

$$M_1 = 200 \text{ GeV} \qquad Y_2 = 143 \text{ GeV}$$

$$m_H = 295.4 \text{ GeV} \qquad \sin^2\theta_L^b = 0.00811$$

$$\alpha_s(M_Z) = 0.116$$



New neutral gauge bosons (Z')

Example: $SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_{B-L}$

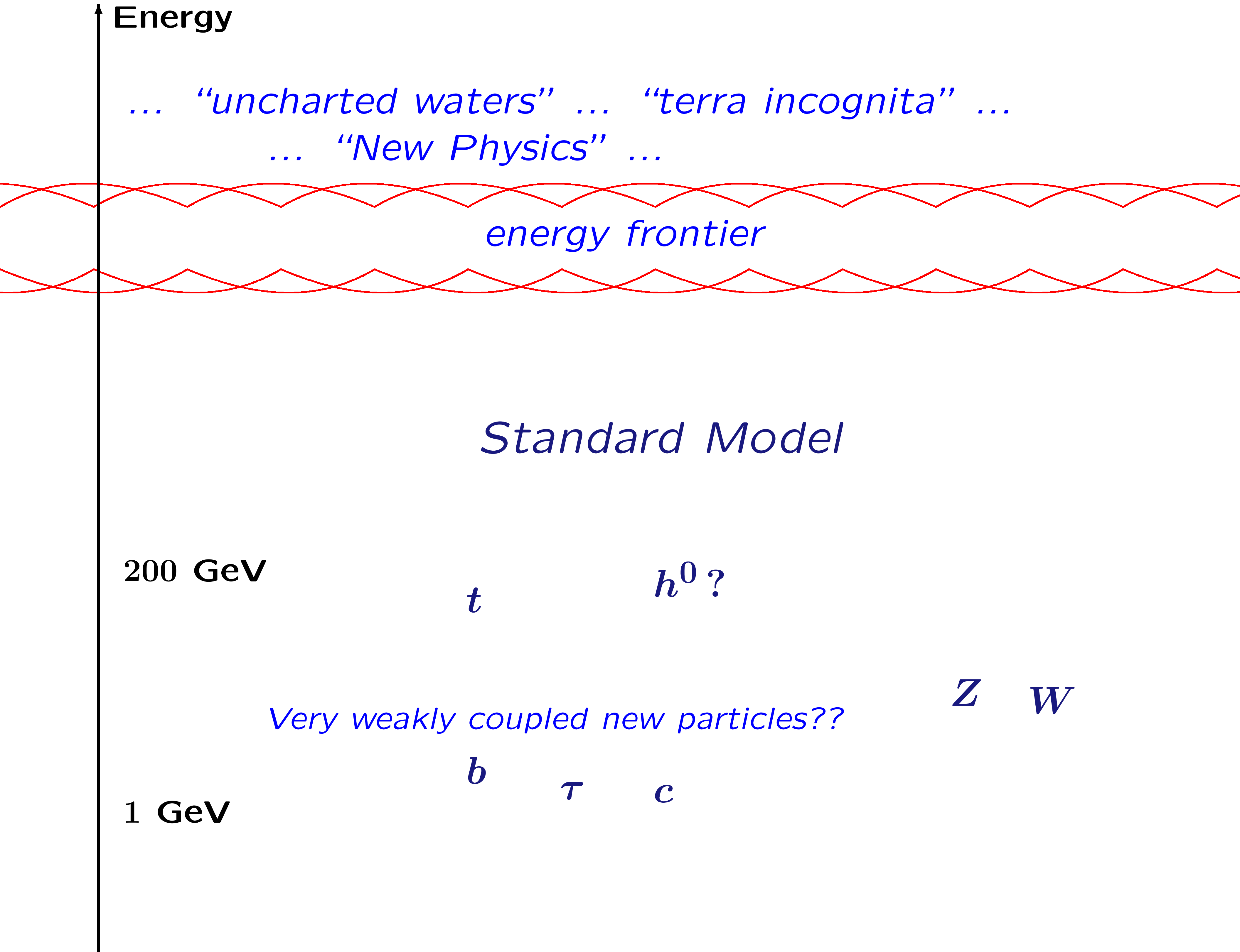
(Appelquist, Dobrescu, Hopper, hep-ph/0212073)

Z_{B-L} **does not mix at tree level with the** Z

Run I: $M_{Z_{B-L}} > 480$ **GeV**

Could be discovered in Run II.

$\longrightarrow$ *Gauge anomaly cancellation would then provide information about* $\boldsymbol{\nu}$ *sector.*


Energy
... “uncharted waters” ... “terra incognita” ...
... “New Physics” ...
energy frontier
Standard Model
200 GeV
t
h^0 ?
Z
W
Very weakly coupled new particles??
b
τ
c
1 GeV

More dimensions

4D flat spacetime $\perp$ one dimension of size πR:

$$\text{Boundary conditions}: \quad \frac{\partial}{\partial y}\phi(x,0) = \frac{\partial}{\partial y}\phi(x,\pi R) = 0$$

$$\Longrightarrow \quad \phi(x,y) = \frac{1}{\sqrt{\pi R}}\left[\phi^0(x) + \sqrt{2}\sum_{j\geq 1}\phi^j(x)\cos\left(\frac{jy}{R}\right)\right]$$

Kaluza-Klein modes, $\phi^j(x)$: particles with momentum in extra dimensions

$\Rightarrow$ massive particles in 4D: $m_j^2 = m_0^2 + \dfrac{j^2}{R^2}$

Fermions in a compact dimension

Lorentz group in 5D $\Rightarrow$ vector-like fermions:

$$\chi = \chi_L + \chi_R$$

Chiral boundary conditions:

$$\begin{aligned} \chi_L(x^\mu, 0) &= \chi_L(x^\mu, \pi R) = 0 \\ \frac{\partial}{\partial y}\chi_R(x^\mu, 0) &= \frac{\partial}{\partial y}\chi_R(x^\mu, \pi R) = 0 \end{aligned}$$

Kaluza-Klein decomposition:

$$\chi(x, y) = \frac{1}{\sqrt{\pi R}}\left\{\chi_R^0 + \sqrt{2}\sum_{j\geq 1}\left[\chi_R^j \cos\left(\frac{\pi j y}{L}\right) + \chi_L^j \sin\left(\frac{\pi j y}{L}\right)\right]\right\}$$

Universal Extra Dimensions

T. Appelquist, H.-C. Cheng, B. Dobrescu, Phys.Rev.D64 (2001)

All Standard Model particles propagate in $D \geq 5$

Momentum conservation $\Rightarrow$ KK parity is conserved

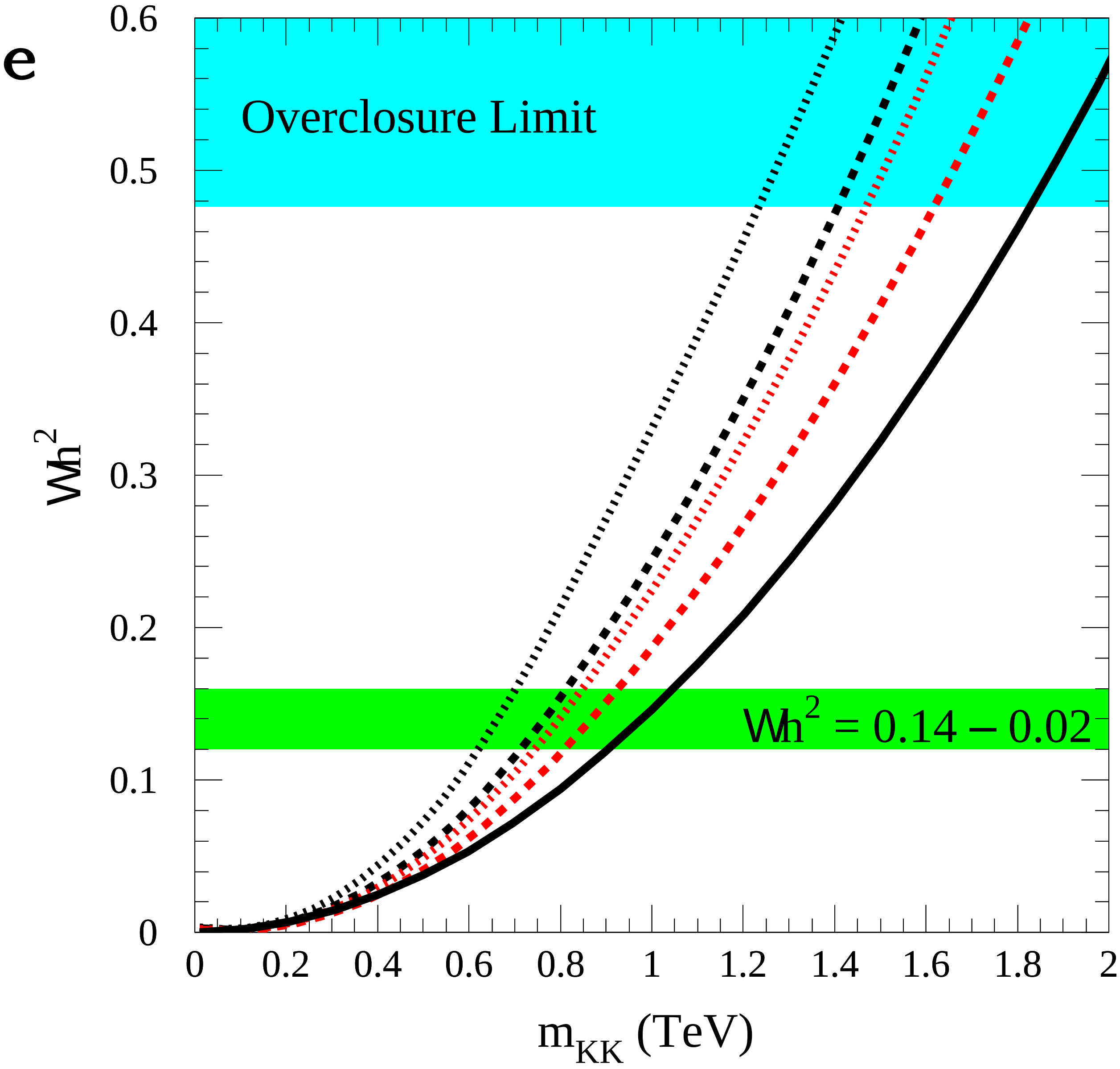
- **Bounds from one-loop shifts in M_W/M_Z and other observables: $\frac{1}{R} \gtrsim 300\ \mathrm{GeV}$**
- **Pair production of Kaluza-Klein modes at colliders: could be discovered soon!**

(Cheng, Matchev, Schmaltz, hep-ph/0205314)

Lightest KK particle is stable in UED:

$\gamma^{(1)}$ is a viable dark matter candidate

(from Servant, Tait, hep-ph/0206071)



Many other models in extra dimensions:

e.g., **"Opaque branes" - localized operators** (Carena, et al, 2002)

Six-Dimensional Standard Model

work with T. Appelquist, G. Burdman, E. Ponton, E. Poppitz, H.-U. Yee

$D = 6$ **(two universal extra dimensions) is special...**

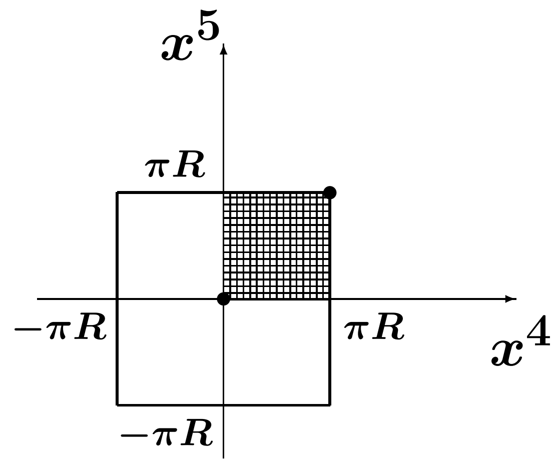
- **Global $SU(2)_W$ anomaly cancellation requires 3 mod 3 generations!**

- **Gravitational anomaly cancellation in 6D requires one right-handed neutrino per generation.**

- **6D Lorentz symmetry allows ν masses only of the Dirac type.**

Compactification of two extra dimensions

Square torus of radius R:



6D Lorentz symmetry broken by compactification:

$$SO(5,1) \longrightarrow SO(3,1) \times Z_8$$

Dominant baryon-number violating processes:
$p \rightarrow e^- \pi^+ \pi^+ \nu\nu$ and $n \rightarrow e^- \pi^+ \nu\nu$

$$\tau_p \approx \frac{10^{35}\mathrm{yr}}{C_{17}^2} \left[\frac{(4\pi)^{-7} 10^{-4}}{\Phi_5 F(\pi\pi)}\right] \left[\frac{1/R}{0.5\ \mathrm{TeV}}\right]^{12} \left[\frac{R M_s}{5}\right]^{22}$$

Long-live the proton!

Message to everybody

- The fundamental laws of nature are very simple compared to the complexity of the universe.

- The fundamental laws of nature that we currently know may be approximations to a set of more profound principles which high-energy physicists could reveal by doing more research.

- The exploration of the energy frontier leads necessarily to discoveries!